

CONF-801038--11

LA-UR -80-2863

TITLE: IN-PLACE TESTING OF TANDEM HEPA FILTER STAGES USING FLUORESCENT AEROSOLS

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SUBMITTED TO: 16th DOE Nuclear Air Cleaning Conference,  
San Diego, CA, October 20-23, 1980

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#### IN-PLACE TESTING OF TANDEM HEPA FILTER STAGES USING FLUORESCENT AEROSOLS\*

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#### Abstract

Fluorescent test aerosols were used in field testing of large multiple-stage HEPA filter systems. The technique excluded interference from non-fluorescent background particles known to leak into the plenum or ducting between the filters and the downstream sampling probe. This technique solved the problem of measuring extremely low concentrations of the test aerosol in the presence of background aerosol.

The upstream fluorescent test aerosol was diluted with clean air and drawn into a single particle aerosol spectrometer capable of counting, sizing, and detecting fluorescence of each particle. The particle sizing function was performed on light scattered by the particle passing through the beam of a helium-cadmium laser. Concurrently the fluorescence excited by the laser illumination was detected at a longer wavelength. Since spectrometer response in the fluorescent mode was <2 percent of naturally occurring aerosols, background aerosols were insignificant as an interference to the downstream concentration measurement. Decontamination factors (DF) on the order of  $10^8$  were measured in the field studies on >9.4 m<sup>3</sup>/s (20,000 cfm) systems. Additional generator capacity and acceptably lower test aerosol to background aerosol concentration ratios could be used to extend this capability to measure DF greater than  $10^8$ .

Dye-tagged DOP aerosols were generated either by gas-thermal or sonic nozzle generators. Experiments with the gas-thermal generator showed only 20 percent of fluorescence from the dye was degraded by the vaporization process. A single sonic nozzle was shown to aerosolize 0.7-1.0 L/hr of dye-tagged DOP aerosol in the proper size range for HEPA filter testing. A multiple sonic nozzle generator is a practical consideration to provide greater capacity.

#### 1. Introduction

This project was directed toward development of new methods of in-place testing of air cleaning systems containing multiple stages of high efficiency particulate air (HEPA) filters. Earlier work produced a highly sensitive method for testing two stages of HEPA filters with a capacity of up to 14.2 m<sup>3</sup>/s (30,000 cfm) using a single-particle, particle-size spectrometer(1) in combination with

\*Work supported by the Office of Nuclear Waste Management and performed at the Los Alamos Scientific Laboratory operated under the auspices of the US Department of Energy, Contract No. W-7405-ENG-36.

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an aerosol diluter.<sup>(2,3)</sup> Usefulness of this method in testing some systems was restricted by extraneous aerosol leaking into the downstream structure, causing an excessive background count. Development of an aerosol spectrometer which could detect a tagged or self-identifying test aerosol was undertaken. Coordinating its development directly with an instrument manufacturer has made the fluorescent particle spectrometer immediately available.

Testing an air cleaning system as a unit was considered advantageous over stage-by-stage tests using the less-sensitive photometer method of ANSI/ASME Standard N510<sup>(4)</sup> for the following reasons: future air cleaning systems could be simplified and made more compact; existing systems could be tested without need for auxiliary ducts and valves to inject challenge aerosol between the first and second stages; testing could proceed without interruption of system operations; and a conservative decontamination factor (DF) of the system could be determined without the possibility of overestimation when individual stage DF's are multiplied together. This overestimation was attributed in earlier testing<sup>(3)</sup> to challenging the second stage with an aerosol containing larger particle sizes normally removed by the first stage.

The additional sensitivity which made the laser spectrometer method applicable to high DF measurement was gained from the complete lack of instrument noise in its digital counting electronics and from its ability to integrate particle count over any required time period. Its particle sizing capability allowed determination of system DF in terms of the ratio of upstream to downstream particle count or volume (mass) in any particle size interval, rather than the ratio of integrated values of instantaneous light scattering signals from an aerosol which undergoes major size change during filtration. Improved accuracy is inherent in the method, although the need for aerosol dilution adds a source of error which offsets this gain somewhat. A disadvantage of the spectrometer method was the more complex, more expensive, and less rugged nature of the spectrometer equipment; however, extensive field testing showed this to be a manageable problem.

### II. Experimental Apparatus and Techniques

Typical system arrangement for testing a two-stage filter system is shown in Fig. 1. Upstream and downstream sampling locations should be selected in conformance with aerosol mixing and sampling recommendations in ANSI/ASME N510.<sup>(4)</sup> The spectrometer and dilution systems are described in detail as their use was applied to several phases of the experimental program. The photometer is considered optional for continuously monitoring dilution ratio.

#### Description of Fluorescent Particle Spectrometer

The laser fluorescent particle size spectrometer, PMS Model ASAS-XF (Particle Measurement Systems, Inc., Boulder, CO.), was designed to identify tagged (fluorescent) particles over a size range of 0.125 to 3.1  $\mu\text{m}$  diameter. Two selectable ranges covered this total range, with each range having fifteen linear size intervals. The light source for the sizing of particles was a 10 mW

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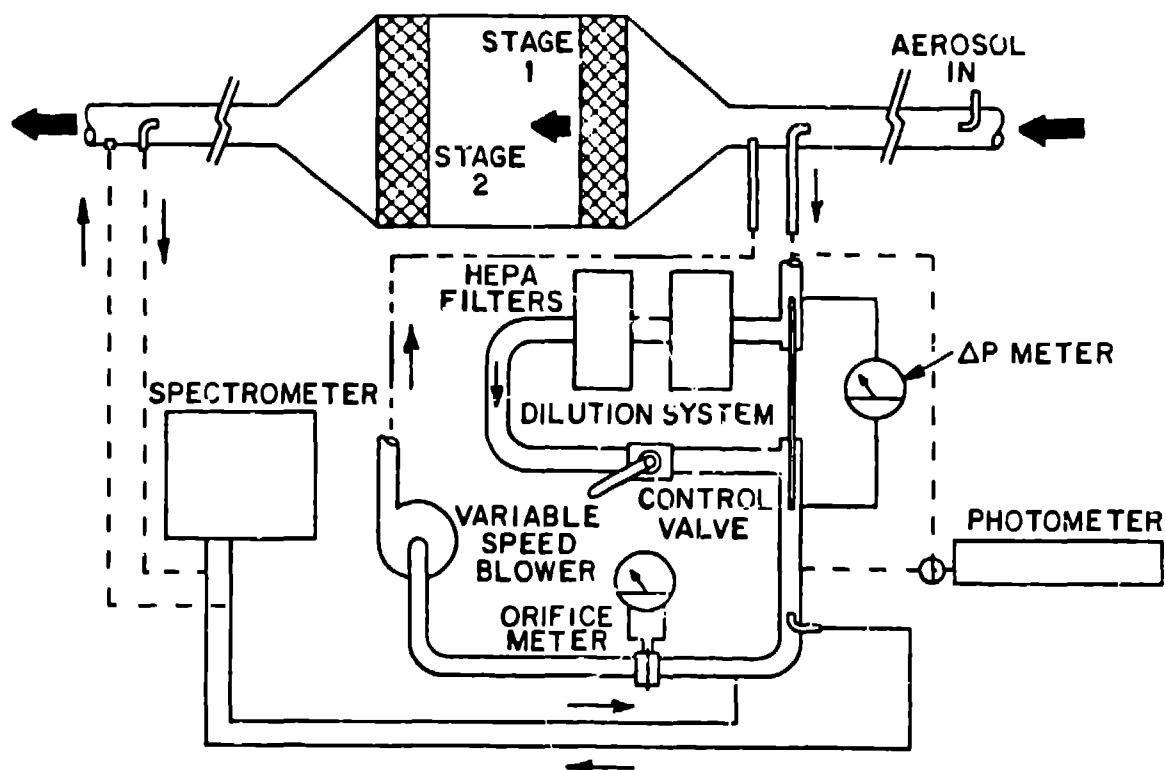


Figure 1.  
HEPA filter test system connection.

HeCd laser operating at a wavelength of 442 nm (blue light) while the fluorescent detection wavelength was greater than 475 nm. This separation between laser (excitation) and fluorescent (emission) wavelengths allowed separate detection of the scattered light for sizing a particle and the emitted light for fluorescent identification.

The optical system is shown schematically in Fig. 2. Light scattered from a particle passing through the active volume of the spectrometer was collected by a parabolic mirror over the angle 35° to 120° and directed to a photomultiplier via mirror and beamsplitter. Intensity of the light pulse was proportional to the physical diameter of the particle, allowing pulse amplitude to be used as a measure of particle diameter. The output of the preamplifier was applied to a pulse height analyzer composed of sixteen voltage comparators and latches. As a voltage pulse was received and sized, it was counted in an appropriate channel of a 16 channel accumulating memory. Coincident with sizing, light emitted from a fluorescent particle at the longer wavelength was producing a pulse from the fluorescent photomultiplier which enabled a count to be registered when the mode selector was set for fluorescent counting. Either fluorescent (FL) or all particle (ALL) mode could be selected by positioning a single switch. At the end of each sampling interval, the final count values were printed on a paper tape record along with time-of-day and total elapsed time. A built-in oscilloscope

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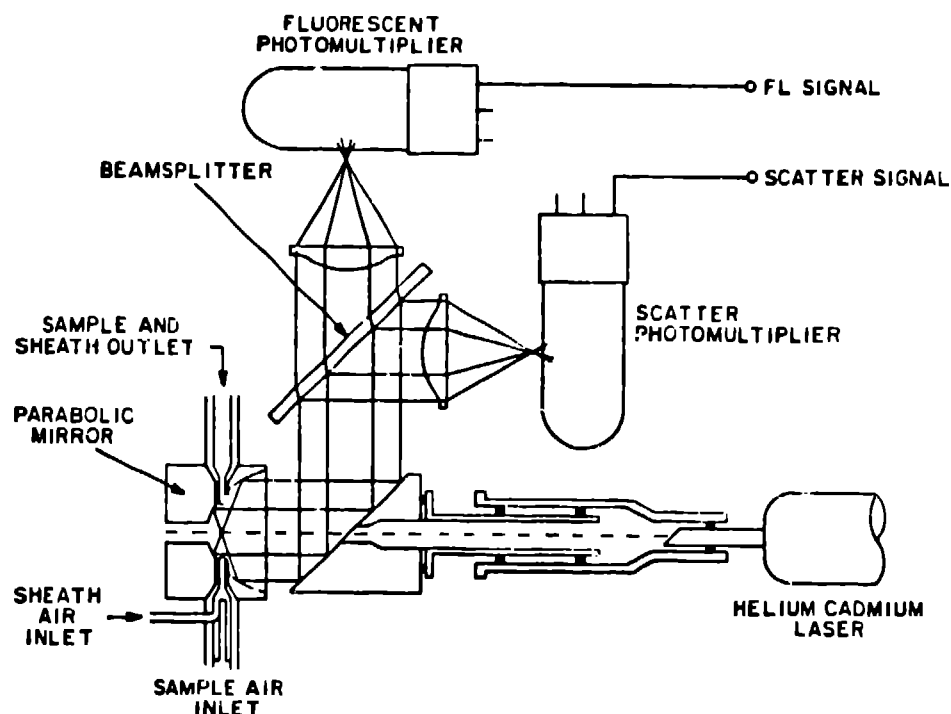


Figure 2.  
ASAS-XF optical system diagram  
(courtesy of Particle Measurements Systems).

displayed a histogram of particle size distribution which could be frozen at any time to allow detailed analysis of a distribution. Counting rate limitations were observed to avoid entering a non-linear region. This occurred at counting rates above  $10^4/\text{s}$  where more than one particle was consistently in the active volume at one time. Sampling flowrate was  $3.0 \text{ cm}^3/\text{s}$  (maximum). Clean sheath air was used to surround the hydrodynamically focused, particle-laden airstream as it entered the laser beam. Laminar flow conditions and isokinetic merging of the two airstreams restricted turbulence and mixing within the sample inlet. Sampling flow and sheath flow rotameters were calibrated using a precision bubble meter and were found to be within  $\pm 4$  percent over their ranges.

Calibration of the ASAS-XF spectrometer was performed by the manufacturer using twenty monodisperse aerosols of polystyrene latex spheres (Dow Chemical Corp., Midland, MI). A possible difference in response of the spectrometer due to difference in refractive index of the DOP aerosol used in field testing (1.50) and the polystyrene spheres used in calibration (1.58) was investigated by the manufacturer. His Mie scattering calculations indicate DOP particles would be sized with approximately  $+0.02 \text{ }\mu\text{m}$  error near the  $0.10 \text{ }\mu\text{m}$  calibration point and  $+0.2 \text{ }\mu\text{m}$  at the  $1 \text{ }\mu\text{m}$  calibration point; i.e., a  $1 \text{ }\mu\text{m}$  DOP particle would be registered one channel above a  $1 \text{ }\mu\text{m}$  polystyrene particle. Since the DOP test aerosol was almost totally composed of droplets smaller than  $1 \text{ }\mu\text{m}$ , this source of error was considered to be insignificant.

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The ASAS-XF laser spectrometer was contained in three packages; one for the laser optical system (18.6 kg, 41 lbs), a second for the electronics enclosure (25.5 kg, 56 lbs), and the third for the laser power supply (5 kg, 11 lb). These packages were cart-mounted for use in the field as shown in Fig. 3 and were easily transported. Operational problems were not serious, involving occasional misalignment of the parabolic mirror aperture. Readjustment of this aperture required 5-10 min. Cleaning of optics was rarely required.

### Sample Dilution

The limitations on count rate specified for the fluorescent particle spectrometer prohibited direct upstream sampling of the challenge concentration required to test large two-stage HEPA systems. Dilution of the sample on the order of 500 to 700 was required. A suitable dilution system was developed with adjustable dilution over the range 500 to 1000. This system, shown schematically in Fig. 1 and also in Fig. 3, provided a diluted sample for the spectrometer from a sidestream duct which responded to pressure fluctuations in the main duct. Connecting the suction and exhaust of the dilution system to the main duct avoided fluctuations in sampling flow noted in earlier dilution systems. Nominal dilution system flow rate was  $0.0024 \text{ m}^3/\text{s}$  (5 cfm), induced by an  $0.038 \text{ m}^3/\text{s}$  (20 cfm) variable-speed, centrifugal blower. This blower was oversized to accommodate the heavily negative static pressure in some HEPA filter systems [up to  $-38 \text{ cm}$  (15 inches) wg]. The major portion of the dilution stream was directed through two HEPA filters ( $0.012 \text{ m}^3/\text{s}$ , 25 cfm capacity) and was recombined with the small unfiltered sample stream passed through a small diameter tube ( $0.162 \text{ cm}$  diam, 33 cm long). Differential pressure measurement across a standard orifice meter provided flow indication. Dilution ratio was selected by setting differential pressure across the small diameter tube by positioning the ball valve. The dilution ratio measurement was calibrated by determining the ratio of light scattering intensity upstream and downstream of the small diameter tube. This calibration indicated an expected error (one standard deviation) of approximately  $\pm 7$  percent at dilution ratios 700 and above, and  $\pm 2$  percent at dilution ratios of 500 or less. This was compatible with the expected error of the DF measurement across two HEPA filter stages. Particle size characteristics (cmd and  $\sigma_g$ ) upstream of the diluter were reduced less than 5 percent by passage through the diluter. Actual particle losses in the tube were accounted for in the calibration procedure.

### Fluorescent Dye Selection

Features of interest in selection of a dye tag were solubility of the dye in DOP, fluorescent intensity at ambient temperature, adequate separation between excitation and emission wavelengths, and retention of fluorescence during aerosol generation from a high-capacity, gas-thermal generator. Potomac yellow No. 838 (Dayglo Color Corporation, Cleveland, OH) was selected over many other dyes after its tag was readily detected in small droplets ( $0.15 \text{ }\mu\text{m}$  diam) by the laser fluorescent particle spectrometer. It had a 440 nm excitation wavelength, well within the band width of the HeCd laser of the fluorescent particle spectrometer, and an emission wavelength of 490 nm, adequately separated from the excitation wavelength for

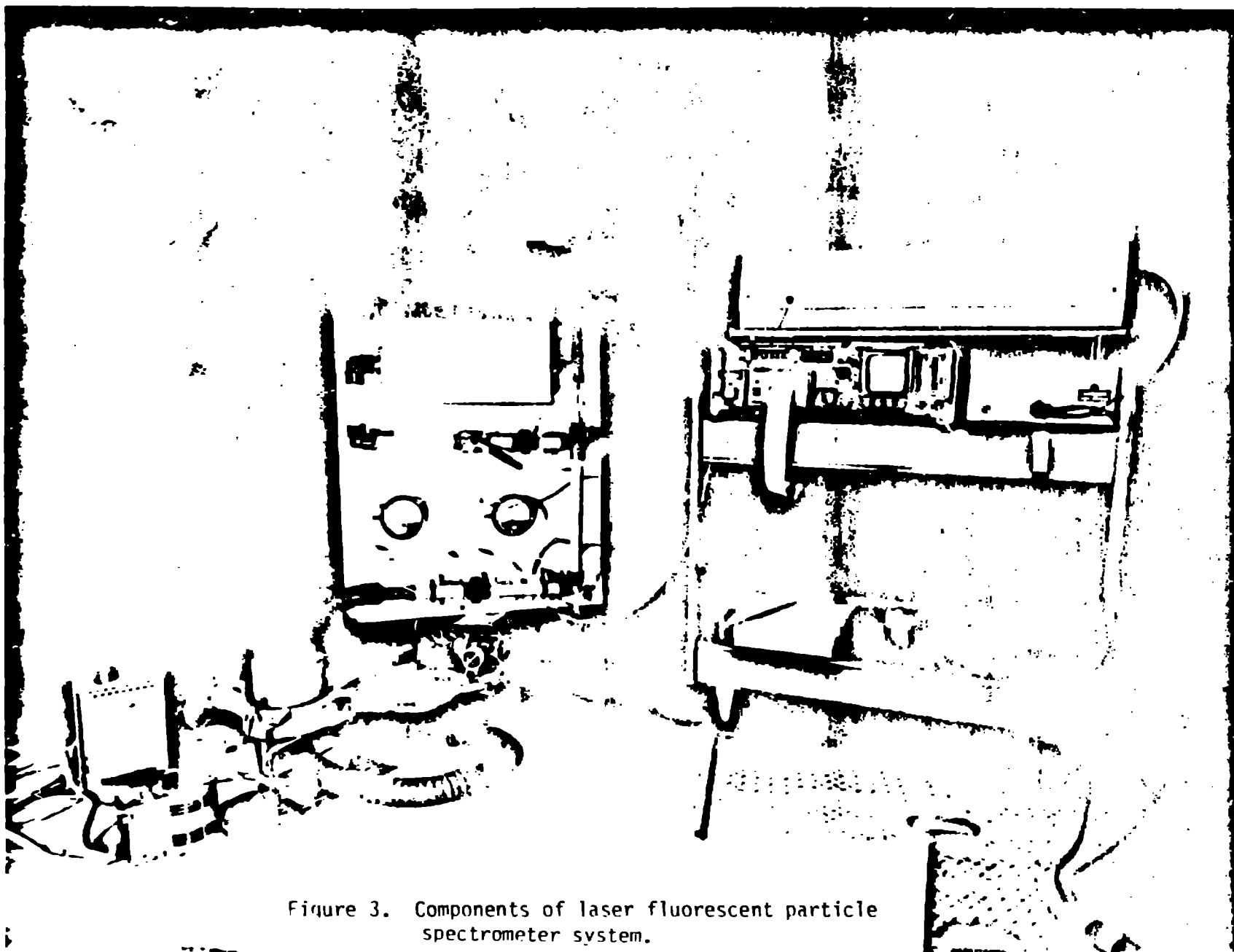


Figure 3. Components of laser fluorescent particle spectrometer system.

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discrimination by the spectrometer. Solubility of Potomac yellow dye in DOP was determined to be 2.0 g/L. This amount of dye was best dissolved by heating the DOP to 90°C for approximately one hour.

### Fluorescent Aerosol Background

Naturally occurring or spurious fluorescent particles were known to be present in the atmosphere and in the ventilation systems of buildings. The effect of these particles on the fluorescent particle test method was evaluated by sampling the background aerosol in open building areas, in ventilation ducts both upstream and downstream of HEPA filter systems in buildings housing chemical and metallurgical research, and at several locations outdoors. The laser fluorescent particle spectrometer was used in both FL (fluorescent) and ALL (all particle) modes to provide the FL/ALL particle ratio. The highest FL/ALL value was 0.016 encountered in open building areas. The lowest value was 0.007, measured outdoors at 1.6 m above ground level. At the sampling points downstream of two HEPA filter stages, only once in 20 counting periods of 10 min each was a fluorescent particle registered by the spectrometer. These data confirmed that the fluorescent particle background downstream was negligible.

### Aerosol Generation

Dye-tagged aerosols suitable for testing HEPA filters were generated using two methods: (1) gas-thermal generation in which bulk solution containing the DOP and the dye are vaporized and recombined in condensed droplets of the proper size and (2) atomization generation by acoustic or sonic breakup of droplets into smaller droplets. A sonic nozzle generator was developed to produce large quantities of dye-tagged particles without need for vaporization. A sonic nozzle [Sonicore No. 035 (Sonic Development Corporation, Upper Saddle River, NJ)] was mounted in a generator assembly as shown in Fig. 4. This nozzle directed a jet of compressed air containing large droplets of DOP into an acoustic cavity<sup>(5)</sup> where a sonic standing wave broke up the droplets and directed the fog outward toward the wall of the horizontal cylinder. Larger drops impinged on the cylinder wall, requiring collection of DOP in a drain bottle for recycling. A small fan provided airflow to remove the aerosol from the generator.

Fig. 5 shows performance characteristics of the sonic nozzle generator at an optimized primary air pressure of  $4.1 \times 10^5$  Pa (60 psig). The feedrate increased with fluid pressure to a maximum of approximately 17 ml/min at  $1.1 \times 10^5$  Pa (16 psig) and above. Losses of large droplets impinging on the generator walls and recovered in the drain bottle reached a peak of 41 percent at  $1.1 \times 10^5$  Pa (16 psig) and decreased at higher pressures. Optimum settings provided particle concentration of  $2.6 \times 10^5$  particles per  $\text{cm}^3$ , adequate for testing 0.47  $\text{m}^3/\text{s}$  (1000 cfm) systems. Larger systems would require several nozzles mounted in the same generator. Particle size characteristics over this fluid pressure range averaged  $0.27 \pm 0.04 \mu\text{m}$  [ $\pm 1$  std dev on 46 values of count median diameter (cmd)]. Mean geometric standard deviation of the DOP aerosol over the same pressure range was  $1.55 \pm 0.06$  ( $\pm 1$  std dev). A single



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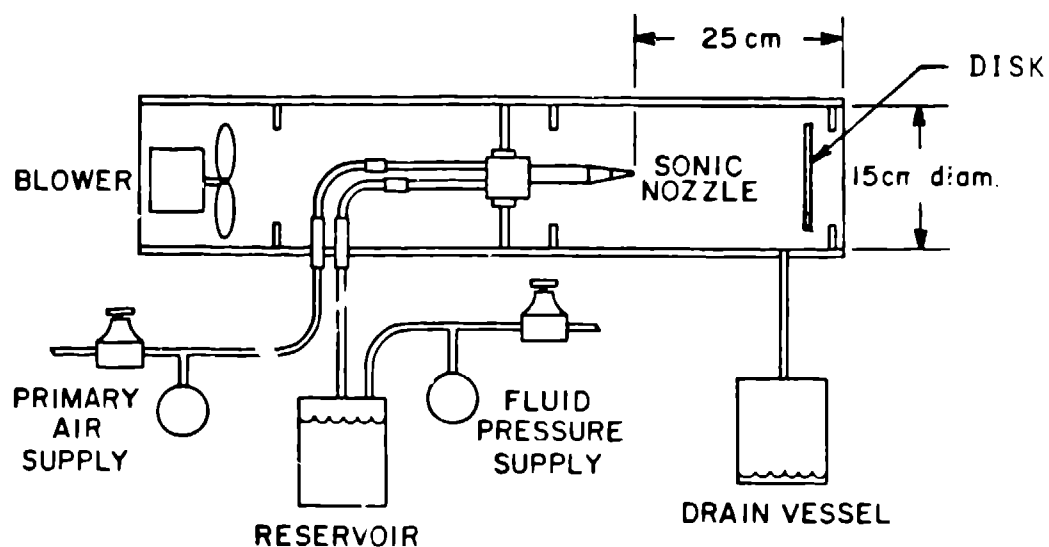


Figure 4.  
Sonic nozzle aerosol generator.

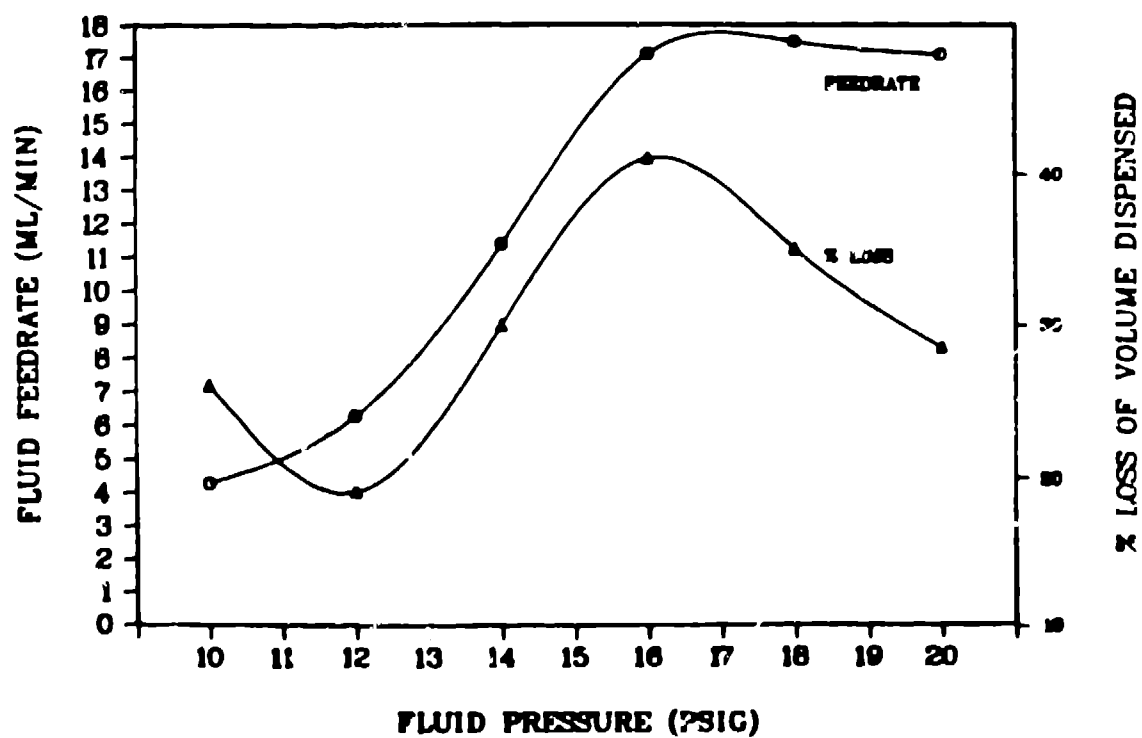


Figure 5.  
Performance characteristics of the sonic nozzle generator.

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sonic nozzle generator required only  $9.4 \times 10^{-4} \text{ m}^3/\text{s}$  (2 cfm) compressed air and a 115 Vac supply for its operation and provided a convenient, high-output source of liquid droplet aerosol.

Higher feedrates and smaller particle size distributions were obtained with two versions of a gas-thermal generator in which a mixture of  $\text{CO}_2$  gas and the dye-DOP solution was forced under pressure into a vaporization chamber operating at approximately  $315^\circ\text{C}$ . As the  $\text{CO}_2$  - DOP vapor mixture exits the generator through a jet, it cools and condenses on available condensation nuclei in room air, forming a dense cloud. The smaller of these generators, the Cloud-maker (Model 11-48, Testing Machines, Inc., Amityville, NY) provided a feedrate of 10 ml/min with none of the wall losses noted with the sonic nozzle generator. Average FL/ALL particle ratio for this generator was  $0.78 \pm 0.10$ , as some particles were not counted as fluorescent. Size characteristics of the aerosol were the same whether sized in the FL or ALL particle mode of the spectrometer, indicating that loss of fluorescence was not size dependent. Size characteristics of the DOP aerosol from the small gas-thermal generator were  $0.20 \pm 0.01 \text{ } \mu\text{m}$  ( $\pm 1$  std dev) cmd and  $1.24 \pm 0.04$  ( $\pm 1$  std dev)  $\sigma_g$ , indicating the gas-thermal generator produces a smaller and narrower size distribution than the sonic nozzle generator. Number concentrations as high as  $5 \times 10^6$  particles/ $\text{cm}^3$  were generated consistently.

A high-capacity, gas-thermal (HCGT) generator was developed for use in field testing large HEPA filter systems. One of several configurations of HCGT generator is shown in Fig. 6. Some difficulty in obtaining high, steady numbers of fluorescent particles was encountered at DOP feedrates above 60 ml/min, although the generator produced satisfactory DOP aerosol at higher feedrates for non-fluorescent particle testing. Fluorescence quenching was attributed to gradual cooling of the vaporization chamber below the temperature at which the dye would vaporize. The solid dye particles left after evaporation of the DOP carrier would then only occasionally recombine with a freshly condensed DOP droplet to give it a dye tag. Further modifications of the HCGT generator are expected to render it more stable at higher feedrates. Particle size characteristics of the HCGT generator were similar to the smaller generator characteristics, yielding  $0.19 \pm 0.02 \text{ } \mu\text{m}$  ( $\pm 1$  std dev) cmd, and  $1.22 \pm 0.04$  ( $\pm 1$  std dev)  $\sigma_g$ . The FL/ALL ratio for the HCGT generator was  $0.77 \pm 0.08$  ( $\pm 1$  std dev). As discussed later, this fluctuation in FL/ALL required several checks during field testing to assure consistent results.

### Decontamination Factor and Uncertainty Calculations

Performance of each two-stage filter system was calculated in terms of decontamination factor DF by the equation:

$$\text{DF} = \frac{\text{DC}_D}{t_D} \left( \frac{C_{ds}}{t_{ds}} - \frac{B_{ds}}{t_B} \right)^{-1} \quad (1)$$

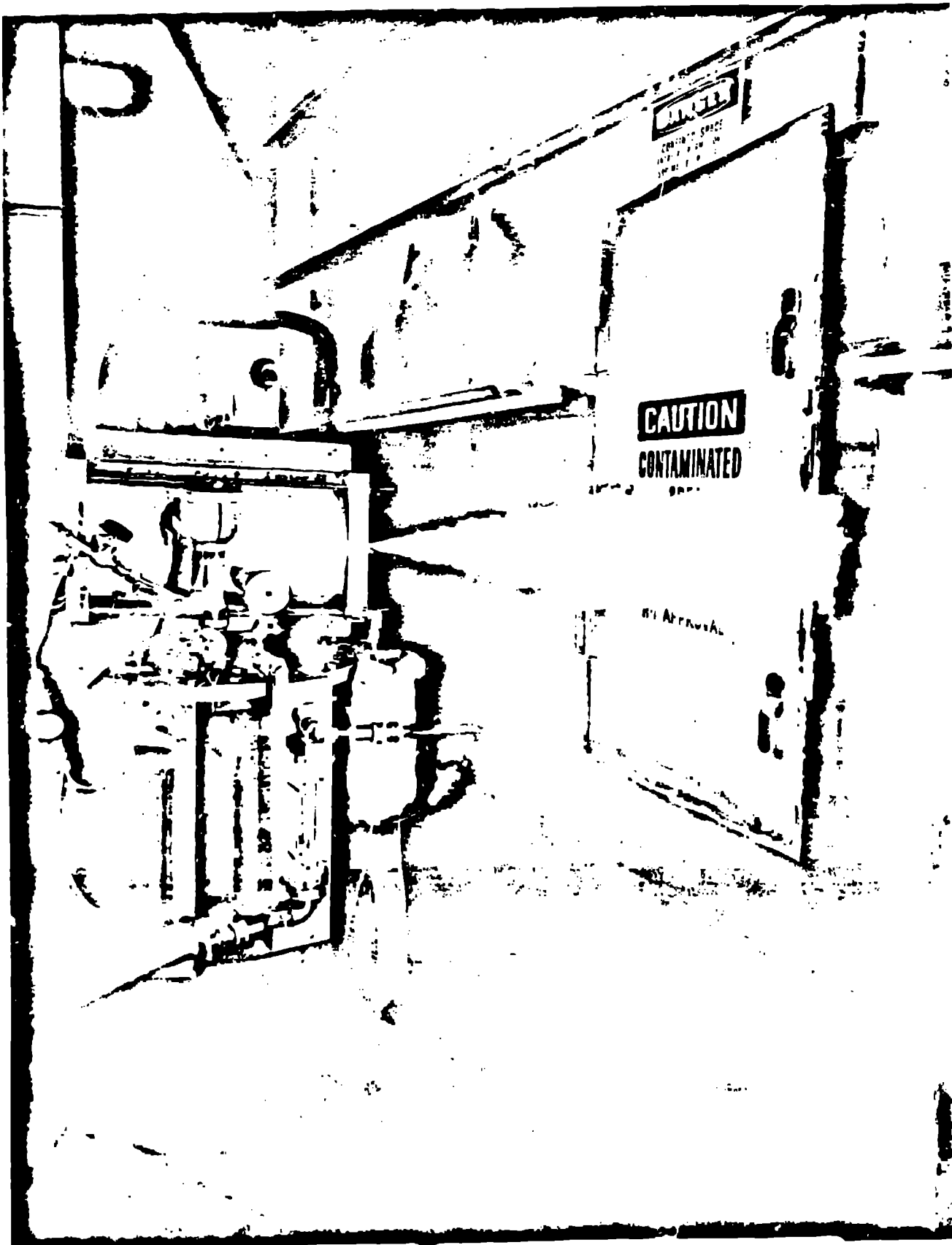


Figure 6. High-capacity, gas-thermal aerosol generator.

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where  $D$  = dilution ratio,  
 $C_d$  = total count in the diluter (upstream sample),  
 $t_d$  = upstream sampling time,  
 $C_{ds}$  = downstream total count,  
 $t_{ds}$  = downstream sampling time,  
 $B_{ds}$  = downstream background count,  
 $t_B$  = downstream background sampling time.

Stage 1 decontamination factor by spectrometer was calculated by the following equation:

$$DF_1 = \frac{D C_d}{t_d} \left( \frac{t_1}{C_1} \right) \quad (2)$$

where  $C_1$  = total count downstream of Stage 1.  
 $t_1$  = sampling time downstream of Stage 1.  
 Stage 2 decontamination factor was calculated by the following equation:

$$DF_2 = \frac{C_1}{t_1} \left( \frac{C_{ds}}{t_{ds}} - \frac{B_{ds}}{t_B} \right)^{-1} \quad (3)$$

where the terms were as defined earlier.

The fractional standard deviation ( $\Delta DF/DF$ ) in the decontamination factor measurement across multiple stages was estimated by assuming that the random counting process of the spectrometer was a Poisson process, in which the standard deviation is approximated by the square root of the count number.<sup>(6)</sup> Therefore, the uncertainties based on one standard deviation of downstream count  $C_{ds}$  and downstream background  $B_{ds}$  were expressed as  $\Delta C_{ds} = \sqrt{C_{ds}}$  and  $\Delta B_{ds} = \sqrt{B_{ds}}$ . By assuming equal counting times to obtain  $C_{ds}$  and  $B_{ds}$  and no error in measuring the counting times,  $\sqrt{C_{ds}}$  and  $\sqrt{B_{ds}}$  could be combined as the root mean square of the sum as follows:

$$\frac{\Delta (C_{ds} - B_{ds})}{C_{ds} - B_{ds}} = \frac{(C_{ds} + B_{ds})^{1/2}}{C_{ds} - B_{ds}} \quad (4)$$

By combining this calculated uncertainty with the uncertainty terms for the dilution ratio  $D$  and upstream count  $C_d$ , and assuming these are all random and independent, the uncertainty in  $DF$  of multiple stages became:

$$\frac{\Delta DF}{DF} = \left[ \left( \frac{\Delta D}{D} \right)^2 + \frac{1}{C_d} + \frac{C_{ds} + B_{ds}}{(C_{ds} - B_{ds})^2} \right]^{1/2} \quad (5)$$

The fractional standard deviation in  $D$  was based on one standard deviation of the experimental results of the diluter calibration and subsequent checks. A conservative value for  $\Delta D/D$  was assumed to be

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0.10 in this case. The term  $C_D$  was always large ( $>10^4$ ), permitting the  $1/C_D$  term to be neglected.

The effect of background count on the uncertainty of the DF measurement was calculated by Equation (5) to determine what conditions would favor the use of fluorescent particles. Figure 7 shows calculated  $\Delta DF/DF$  as a function of particle count above background ( $C_{ds} - B_{ds}$ ). The error is lowest for the fluorescent particle case ( $B_{ds} = 0$ ) and shows that errors can be maintained below  $\pm 0.50$  by counting downstream until 4 or more counts are collected. In non-fluorescent testing, a background of only 20 counts in a given time interval would require 15 counts above background (approximately 35 total) to maintain the error below  $\pm 0.50$ . These extra counts in all particle mode require counting times 3-4 times that in the fluorescent particle mode.

### III. Experimental Results and Discussion

#### Laboratory Scale HEPA Filter Testing

Following development and calibration of the aerosol dilution system and checkout of the laser fluorescent particle spectrometer, a series of 20 tests of a two-stage,  $0.39 \text{ m}^3/\text{s}$  (820 cfm) HEPA filter system was performed preliminary to the field testing program. Two aerosol generators were used: the small gas-thermal generator for eight tests and the prototype sonic nozzle generator for 12 tests. Decontamination factors (DF) of the two-stage system averaged  $2.5 \times 10^7$  with a standard deviation of  $1.1 \times 10^7$  for 20

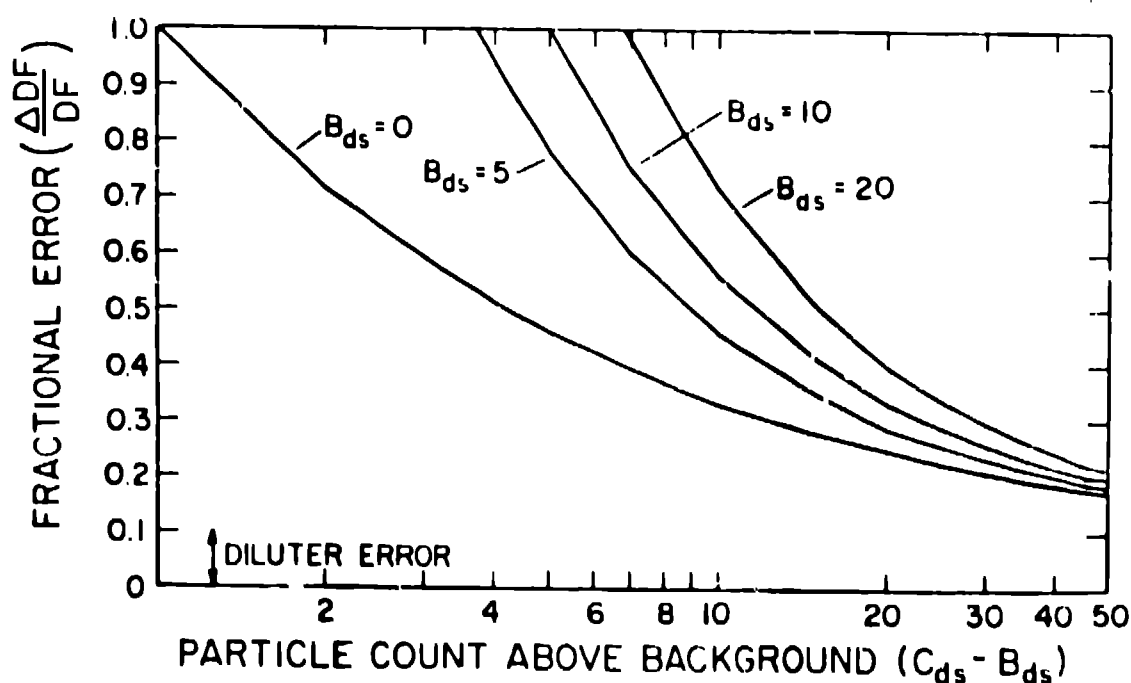


Figure 7.  
Error estimates based on background counts.

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tests. The fractional standard deviation for these 20 tests (0.44) was larger than expected from test data of a single system. However, by selecting data taken when only the small gas-thermal generator was used at a single dilution ratio (700), the fractional standard deviation was only 0.15 for 5 tests.

The DF values above were based on totals of counts in all channels of the spectrometer. Since very few particles in the downstream sample appeared above Ch. 4 ( $>0.30 \mu\text{m}$ ), DF of particles in a narrower size range (Ch. 1,2,3,4) was calculated to determine whether this would provide a significantly different and more conservative result. Where the sonic nozzle aerosol generator was used, DF was reduced by approximately 28 percent; using the small gas-thermal generator, the reduction was only 14 percent since fewer larger particles were generated in the gas-thermal process.

### Field Testing of Large Two-Stage Systems

Decontamination factors of two large two-stage HEPA filter systems at the Chemistry and Metallurgy Research Building, LASL, were measured in FL and ALL modes of the ASAS-XF aerosol spectrometer and by the standard ANSI/ASME N510 photometer method. System FE-14, a 5 x 12 filter system rated at  $28.3 \text{ m}^3/\text{s}$  (60,000 cfm) was operating at  $22.9 \text{ m}^3/\text{s}$  (48,500 cfm) with a nominal pressure drop across Stage 1 of 3.2 cm (1.25 inches) w.g. at the time of testing. System FE-33 was operating at a reduced capacity of  $10.4 \text{ m}^3/\text{s}$  (22,000 cfm) at the time of testing. Pressure drop across its first stage was 1.0 cm (0.4 inches) w.g.

Results of multiple tests of these systems are shown in Figs. 8 and 9. The mean and standard deviation of FE-14 DF were  $0.90 \pm 0.26 \times 10^8$  for three FL tests;  $0.58 \pm 0.26 \times 10^8$  for three ALL tests. The single photometer test yielded  $\text{DF} = 0.27 \times 10^8$  for this system calculated by multiplying the individual DF's of Stage 1 and Stage 2. The mean and standard deviation of FE-33 tests were  $1.6 \pm 1.0 \times 10^8$  for four FL tests;  $2.0 \pm 0.7 \times 10^8$  for four ALL tests. The photometer test of FE-33 yielded a calculated DF of  $5 \times 10^8$ . DF measured by photometer was expected to exceed the spectrometer DF, particularly at Stage 2, due to reduced sensitivity of the photometer to the smaller mean particle size downstream of a filter stage.<sup>(3)</sup> This was not evident in these test results but the photometer results were too few to allow any generalizations to be made. However, the photometer data have been included in Figs. 8 and 9 to show the methods agreed reasonably well (mean values agreed within a factor of three) and all test results exceeded the DOE DF guideline of  $4 \times 10^6$  (99.95 percent efficiency on each of two stages).

Estimates of uncertainty in the FE-14 and FE-33 experimental results were calculated by Equation (5). Downstream FL counts ranged from 6 to 22, accounting for some of the variation in  $\Delta\text{DF}/\text{DF}$  values. The fractional standard deviations ranged from 0.20 to 0.46 for the ALL particle tests and from 0.24 to 0.42 for the FL tests. These experimental uncertainties showed reasonable consistency with the theoretical fractional standard deviations discussed earlier. In general, uncertainties of  $\pm 0.50$  should be expected when measuring DF on the order of  $10^8$ , whether by the non-fluorescent or fluorescent spectrometer method.

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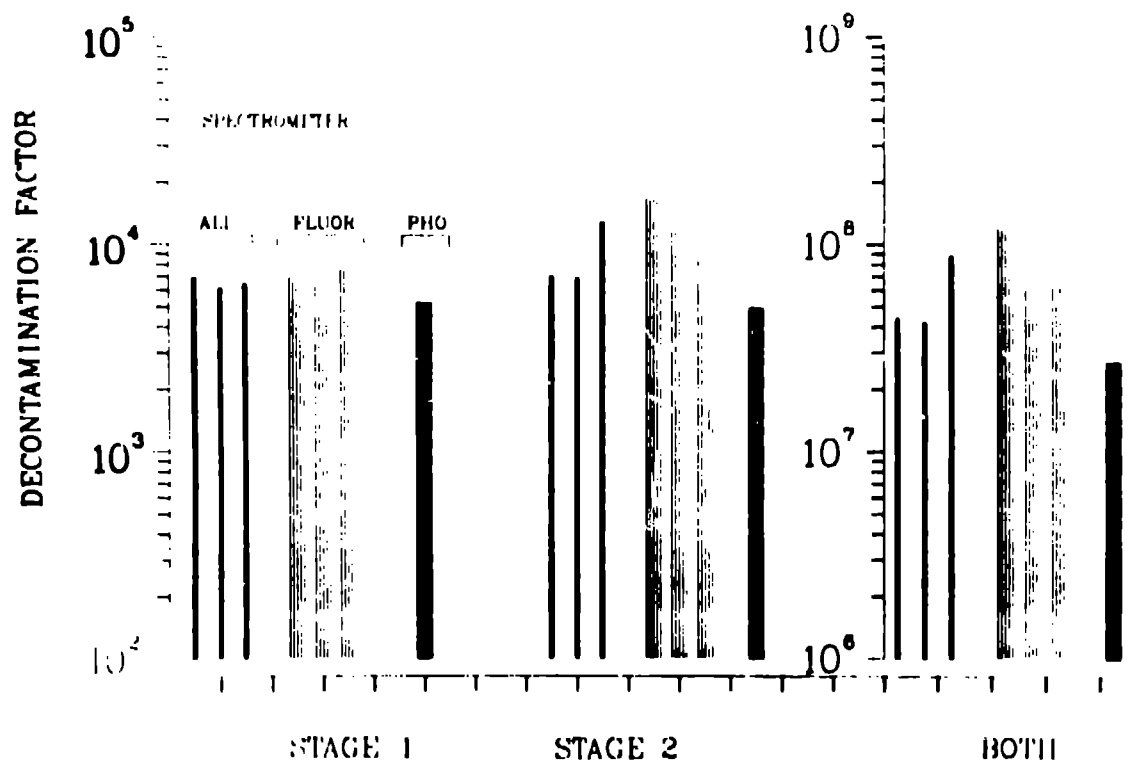


Figure 8.  
Performance of FE-14, a large two-stage HEPA filter system.

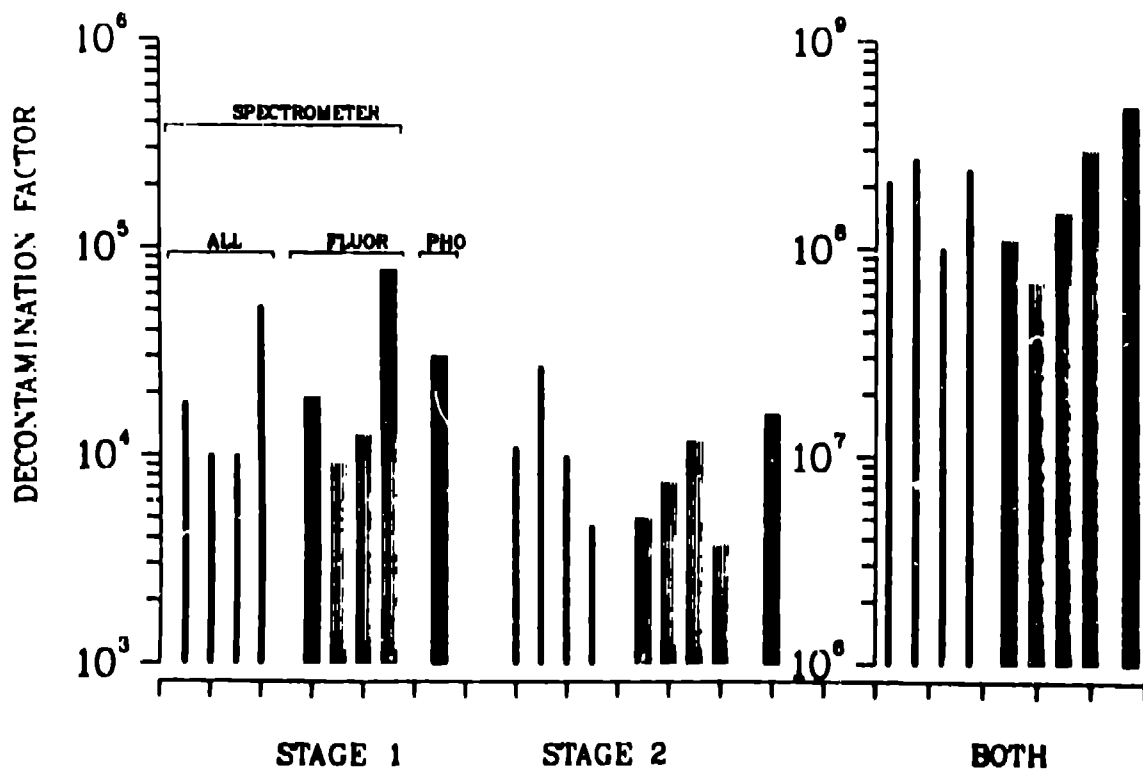


Figure 9.  
Performance of FE-33, a large two stage HEPA filter system.

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These  $\Delta DF/DF$  values indicated no clear-cut advantage was gained by using fluorescent particles to reduce uncertainty in testing these particular systems, nor were sampling times significantly shortened. However, these systems are considered to contain a-typically low background non-fluorescent aerosol concentrations. Future testing of most large two-stage systems is expected to benefit from fluorescent particle use and from improved stability of the HCGT generator.

### Sampling Line Losses

Particle loss in the sampling tube attached to the spectrometer was estimated by sampling a polydisperse DOP aerosol which had undergone filtration through one stage of HEPA filters. All large particles ( $>0.4 \mu\text{m}$ ) were removed by this filtration and the aerosol was rendered similar in particle size characteristics to the aerosol sampled downstream of two HEPA filters. Numbers of particles sized in the first three channels of the spectrometer ( $0.125 - 0.250 \mu\text{m}$ ) were compared by sampling from a chamber using a 33 cm (13 inches) sampling tube and a longer (142 cm, 56 inches) sampling tube. Both tubes were 0.32 cm i.d. plastic tubing. The longer tube was identical in length and configuration to the tube used in the field testing. The sampling tube was connected to a 122 cm, 0.48 cm i.d. sampling probe. Numbers of particles collected with the short tube exceeded the number collected with the longer tube by 2 to 5 percent. This indicated that errors in the particle counting were not large. The sum of losses in the probe and sampling tube was expected to be in the range of 5 to 10 percent; however, a correction factor was not applied to count results since upstream and downstream errors were expected to approximately offset each other.

### Filter Loading

Filter loading as a potential problem in two-stage HEPA filter testing by the fluorescent particle method was monitored during the field tests in terms of differential pressure across the first stage. As a general observation, it was noted that the  $28.3 \text{ m}^3/\text{s}$  (60,000 cfm) systems displayed very little  $\Delta P$  increase during as much as 2 hours generation time if the original  $\Delta P$ 's were low. For example, System FE-33 Stage 1  $\Delta P$  was 1.0 cm (0.40 inches) w.g. at the beginning of testing and 1.12 cm at the end of 100 min; it returned to 1.0 cm within 48 hours of the end of aerosol generation. As an illustration of a system starting with a somewhat higher loading, FE-14 Stage 1  $\Delta P$  started at 2.8 cm w.g. and increased to 3.2 cm after 175 min of testing. This  $\Delta P$  also returned to its original value; while the actual time required was not noted it was less than five days. Although the dye lag must have imposed a permanent loading on the filters, it was not measurable. Loading of a filter system by this test method does not appear to be a significant problem.

### Decontamination Factor As A Function Of Particle Size

The particle counts within each size interval provided by the spectrometer were used to calculate DF of Stage 1 as a function of particle size. The scatter in the data above Ch. 4 prevented correlation with earlier efforts to describe the size of minimum  $DF(2)$ ; however, all DF data from the field study indicate



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continuously diminishing DF over the operating range of the spectrometer, from which the size of minimum DF could be inferred to be below  $0.15\text{ }\mu\text{m}$ . Schuster and Osetek<sup>(2)</sup> placed the size of minimum DF near  $0.19\text{ }\mu\text{m}$  by a similar method under more controlled conditions.

### IV. Summary

A laser fluorescent particle spectrometer has been developed and successfully used to measure decontamination factors of large two-stage HEPA filter systems. The fluorescent tag placed in the DOP test aerosol was detected with high efficiency and eliminated the background aerosol problem which interfered with earlier measurements. Measurements of DF as high as  $10^8$  were accomplished on a  $22.0\text{ m}^3/\text{s}$  (49,500 cfm) system. This indicates the range of sensitivity provided by the fluorescent particle spectrometer method to be sufficiently broad to test most two-stage HEPA systems as single units. Filter loading by the test aerosol was shown to be a minor problem. Although the spectrometer and associated equipment are more complex, more expensive, and less rugged than photometer equipment typically used in filter testing, advantages of the method such as DF measurement more representative of actual filter performance and potential savings in testing costs make the fluorescent particle spectrometer method a useful test method.

### Acknowledgements

The authors recognize and appreciate the cooperation and assistance of John Ortiz, Industrial Hygiene Group, in the performance of the field tests.

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